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Pseudomorphic Semiconducting Heterostructures from
Combinations of AlN, GaN and Selected SiC Polytypes:
Theoretical Advancement and its Coordination
with Experimental Studies of Nucleation, Growth,
Characterization and Device Development

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13. ABSTRACT (Maximum 200 words)

Thin epitaxial films of SiC/AlN multilayers and $(AlN)_x(SiC)_{1-x}$ solid solutions have been grown by plasma-assisted, molecular beam epitaxy between 1050–1300°C using the gas sources of Si_2H_6, C_2H_4 and N_2, the last decomposed using a compact electron cyclotron resonance plasma source, and the solid source of Al. Vicinal $\alpha(6H)$-SiC(0001) was used for the substrates. Electron diffraction and high resolution TEM revealed monocrystalline layers and pseudomorphic growth. Additional studies have shown that (1) the off-axis orientation of the substrate affects the film morphology, (2) surface cleaning is very important and (3) Si/C gas flow ratios may be used to control the SiC polytype. Both $\beta(3C)$- and $\alpha(6H)$-SiC have been successfully deposited on $\alpha(6H)$-SiC substrates. The chemical interdiffusion between monocrystalline AlN films and $\alpha(6H)$-SiC wafers is also under study. The results of the successful research regarding multilayer heterostructures in the AlN/GaN system are now being used to guide the fabrication of a double heterostructure ultra-violet light emitting diode based on suitably doped AlGaN confinement layers with improved carrier confinement and mobility.

14. SUBJECT TERMS

silicon carbide, aluminum nitride, gallium nitride, pseudomorphic heterostructures, molecular beam epitaxy, chemical interdiffusion, surface cleaning, light emitting diode

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Table of Contents

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I. Introduction

The advent of techniques for growing semiconductor multilayer structures with layer thicknesses approaching atomic dimensions has provided new systems for both basic physics studies and device applications. Most of the research involving these structures has been restricted to materials with lattice constants that are equal within $\sim 0.1\%$. However it is now recognized that interesting and useful pseudomorphic structures can also be grown from a much larger set of materials that have lattice-constant mismatches in the percent range. Moreover, advances in computer hardware and software as well as the development of theoretical structural and molecular models applicable for strained layer nucleation, growth and property prediction have occurred to the extent that the field is poised to expand rapidly. It is within this context that the research described in this report is being conducted. The materials systems of concern include combinations of the direct bandgap materials of AlN and GaN and selected, indirect bandgap SiC polytypes.

The extremes in thermal, mechanical, chemical and electronic properties of SiC allow the types and numbers of current and conceivable applications of this material to be substantial. However, a principal driving force for the current resurgence of interest in this material, as well as AlN and GaN, is their potential as hosts for high power, high temperature microelectronic and optoelectronic devices for use in extreme environments. The availability of thin film heterostructural combinations of these materials will substantially broaden the applications potential for these materials. The pseudomorphic structures produced from these materials will be unique because of their chemistry, their wide bandgaps, the availability of indirect/direct bandgap combinations, their occurrence in cubic and hexagonal forms and the ability to tailor the lattice parameters and, therefore, the amount of strain and the physical properties via solid solutions composed of the three components.

The research described in the following sections is concerned with (1) the pseudomorphic nature and microstructural character of AlN/SiC and AlN/GaN layered assemblies, (2) the nucleation and growth mechanisms of SiC and AlN films on the surfaces of each other and (3) the chemical interdiffusion between monocrystalline AlN and SiC. These sections detail the procedures, results, discussions of these results, conclusions and plans for future research. Each subsection is self-contained with its own figures, tables, and references.

II. Growth of Pseudomorphic Heterostructures and Solid Solutions in the AlN-SiC System by Plasma-assisted, Gas-source Molecular Beam Epitaxy

A. Introduction

A marked increase in the interest in wide band gap semiconductor materials for use in high-temperature, -power, -frequency and -speed microelectronic devices resistant to radiation and short-wavelength optoelectronic devices has recently been demonstrated on a global scale. Two candidate materials that have generated much of this interest are SiC and AlN. Two methods of simultaneously exploiting the favorable characteristics of these materials include the thin film deposition of both pseudomorphic heterostructure and alloys.

Pseudomorphic heterostructures of dissimilar semiconductor materials are the basis for quantum well and laser devices. The physical properties (e.g., lattice parameter, crystal structure, melting point and thermal expansion) as well as the optical and electronic properties (e.g., band gap and index of refraction) of SiC and AlN indicate that stable superlattice structures of these materials having the desired properties are feasible. Theoretical calculations regarding electronic structure and bonding at AlN/SiC interface [1] and critical layer thickness prior to misfit dislocation formation at interfaces in cubic AlN and SiC have been reported [2]. Rowland *et al.* [3] have described the growth of 3C-SiC/2H-AlN pseudomorphic layers on α(6H)-SiC(0001) substrates by plasma-assisted, gas-source molecular beam epitaxy (PAGSMBE) using solid Al evaporated from a standard effusion cell and the gases of Si_2H_6, C_2H_4 and N_2. These layers contained a high density of stacking faults and microtwins caused primarily by interfacial stresses and the low stacking fault energy intrinsic to β-SiC.

Solid solutions of AlN and SiC have been achieved by two primary processing routes: reactive sintering of mixtures of powders of a variety of sources and thin film deposition from the vapor phase. Matignon [4] first reported the synthesis of a $(AlN)_x(SiC)_{1-x}$ material. Rafaniello *et al.* [5,6], Ruh and Zangvil [7], Zangvil and Ruh [8,9,10], Kuo and Virkar [11] and Czeka *et al.* [12] have reported 2H solid solutions as well as mixtures of 6H, 4H, and 2H materials and the existence of a miscibility gap as a result of hot pressing and annealing studies with a variety of heat treatment schedules. The tentative phase diagram proposed by Zangvil and Ruh [9] shows a flat miscibilty gap at ≈ 1900 °C between ≈ 20 and 80 wt% AlN. Above this temperature, a 2H solid solution was reported from ≥ 20 wt% AlN. For ≤ 20 wt% AlN, solutions and two phase mixtures of 6H, 4H, and 2H were observed. Thin film solid solutions have been produced in the Soviet Union by Nurmagomedov *et al.* [13] via sublimation of a sintered SiC/AlN compact at ≥ 2100 °C and in the United States by both Jenkins *et al.* [14] using low pressure (10–76 Torr) metalorganic chemical vapor deposition

2

(MOCVD) between 1200–1250 °C using SiH_4, C_3H_8, NH_3, and $Al(CH_3)_3$ carried in H_2 on $\alpha(6H)$-SiC(0001) and Si(100) and by Kern *et al.* [15] by PAGSMBE at 1050 °C using the sources noted previously [3].

B. Experimental Procedure

In the present research, a specially designed and previously described [16] PAGSMBE system was employed to deposit all AlN-SiC thin films on $\alpha(6H)$-SiC(0001) substrates oriented $3.5 \pm 0.5°$ off (0001) toward [11$\bar{2}$0]. The substrates were chemically cleaned before growth in a 10% HF solution for 5 minutes, and loaded immediately into the UHV growth chamber. Sources of Si and C were disilane (Si_2H_6) and ethylene (C_2H_4), respectively. Aluminum (99.9999% purity) was evaporated from a standard MBE effusion cell operated in all cases at 1260 °C. A compact electron cyclotron resonance (ECR) plasma source supplied by ASTeX, Inc., operating at 100 W forward power, was used to decompose N_2 (99.9995% purity). Typical gas flow rates employed for heterostructure growth were 0.1–1.0 sccm Si_2H_6, 0.2–4.0 sccm C_2H_4 (Si/C ratio was varied between 1/1 and 1/4) and 3.5 sccm N_2. Layers of SiC and AlN were grown for 10 and 60 minutes, respectively. For solid solution growth, typical flow rates were 0.5–1.0 sccm Si_2H_6 and 1.0–4.0 sccm C_2H_4. The N_2 (1.0 sccm) was diluted with ultra-high purity Ar (2.5 sccm) to obtain sufficient electron-atom collisions to sustain a plasma. All films were grown between 1050–1300 °C.

Reflection high-energy electron diffraction (RHEED), operating at 10 kV, was used to determine the crystalline quality of the surface of the resulting films. The chemical composition as a function of film thickness was determined using scanning Auger electron spectroscopy (AES). High-resolution transmission electron microscopy (HRTEM) operating at 200 kV was employed to observe the microstructure of the film as well as the film/substrate interfacial region.

C. Results And Discussion

Figure 1 shows a HRTEM micrograph of a 3C-SiC/2H-AlN bilayer/6H-SiC substrate assembly, the former fabricated at 1050 °C. The AlN layer was grown for 10 minutes using 3.5 sccm N_2 and Al evaporated at 1260 °C. The SiC layer was grown for 60 minutes using 0.25 sccm Si_2H_6 and 0.33 sccm C_2H_4. Each of the interfaces is abrupt and uniform and the layers are identically oriented with continuous atom columns indicating that the layers are epitaxial and pseudomorphic. The strain present in the AlN layer, seen as lattice fringe distortion occurs at the steps present on the SiC substrate. The 3C-SiC layer shows several <111> stacking faults. An AES depth profile of composition versus depth is shown in Fig. 2. RHEED and HRTEM analysis indicated all layers to be monocrystalline.
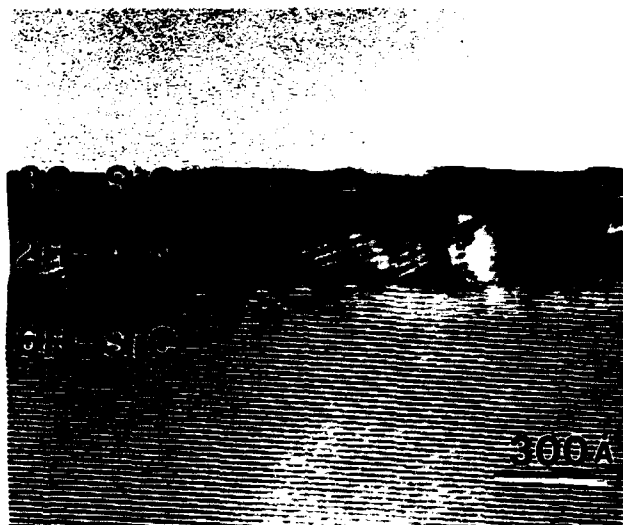
Figure 1. HRTEM image of an epitaxial 3C-SiC/2H-AlN pseudomorphic multilayer on α(6H)-SiC(0001). Shown are positions of lattice distortion due to surface steps in the substrate and dislocations in the film.
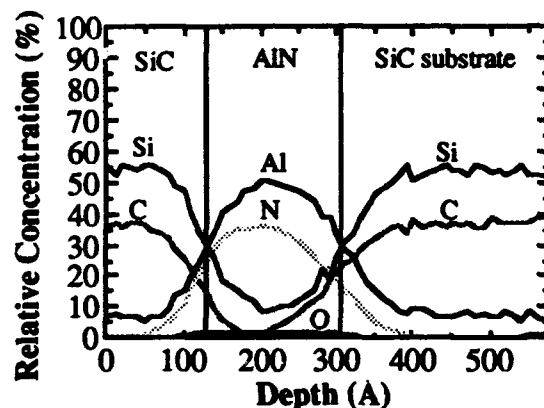

Figure 2. Auger depth profile of SiC/AlN/SiC multilayer.

Figure 3 shows a HRTEM micrograph of a monocrystalline solid solution film grown for 90 minutes at 1275 °C using 0.5 sccm Si_2H_6, 1.0 sccm C_2H_4, 3.5 sccm of Ar-diluted N_2 and Al evaporated at 1260 °C. The ···ABCABC··· stacking sequence indicates that this layer has a cubic crystal structure. RHEED and HRTEM analysis showed the film to be monocrystalline and smooth. The AES depth profile in Fig. 4 indicates the composition to be ≈ $(AlN)_{0.2}(SiC)_{0.8}$. Previous reports by the authors [15], using the same sources, indicated that solid solutions of the composition $(AlN)_{0.3}(SiC)_{0.7}$ resulted in 2H solid solutions. This suggests that a cubic to hexagonal structural change occurs between 20 and 30% AlN for alloys in the AlN-SiC system; however, additional research must be conducted to confirm this hypothesis.
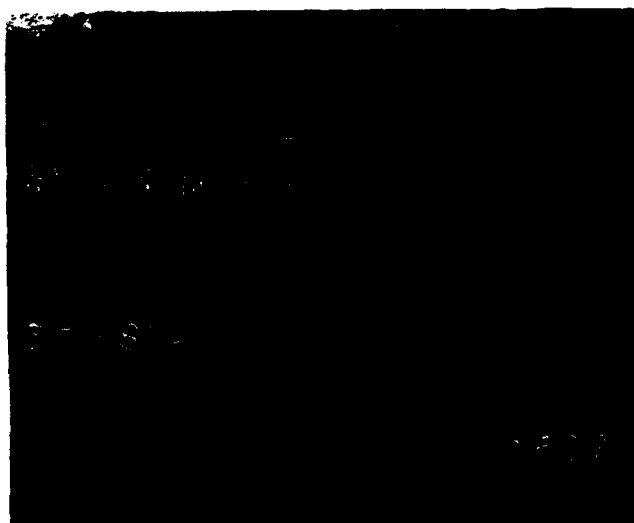
4

Figure 3. HRTEM image of an epitaxial $(AlN)_x(SiC)_{1-x}$ solid solution on $\alpha(6H)$-SiC(0001).

Figure 4. Auger depth profile of an $(AlN)_x(SiC)_{1-x}$ solid solution containing $\approx 20\%$ AlN.

D. Conclusions

Monocrystalline pseudomorphic heterostructures and solid solutions of AlN and SiC have been grown by PAGSMBE on $\alpha(6H)$-SiC(0001) substrates oriented $3.5 \pm 0.5°$ off (0001) toward $[11\bar{2}0]$. The superlattice materials were pseudomorphic and possessed abrupt interfaces; however, lattice distortion was present in the AlN layers and stacking faults occurred in the 3C-SiC layers. Cubic (zincblende) solid solution films containing 20% AlN were also achieved.

E. Future Plans

Studies optimizing growth of SiC on AlN to reduce stacking fault densities and improve crystalline quality are presently underway. Variables such as temperature, flow ratios and pressure are currently being considered. Attempts to grow AlN-rich solid solution films, which would be blue or UV light emitters are also underway.

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III. Growth Mechanisms of SiC Film on 6H-SiC (0001) by Gas-source Molecular Beam Epitaxy

A. Introduction

The growth mechanisms for the SiC film on 6H-SiC by chemical vapor deposition (CVD) is well-established [1, 2]. The 6H polytype of SiC has been obtained on off-axis 6H-SiC substrate under certain conditions. Step flow mechanisms were proposed to explain the homoepitaxial growth of 6H-SiC [1, 2]. According to the model, the stacking sequence of 6H, ABCACB...., can be retained due to the lateral growth which is initiated at the step site on the off-axis substrate. The use of on-axis substrate, therefore, causes the cubic (3C) SiC formation.

Molecular beam epitaxy has been used for the deposition of SiC thin films in order to reduce the growth temperature from that used in CVD (1450–1600°C) on 6H-SiC substrates [3, 4]. Although there has been many successful growth of SiC films in our group [5], the growth mechanisms are unknown. It is significantly important to study growth mechanisms in order to obtain very thin, smooth and defect free films, and to form other polytypes such as 2H- and 4H-SiC.

In this study an attempt has been made to clarify the growth mechanisms through the observation of the initial stage of growth by HRTEM and *in situ* RHEED oscillation.

B. Experimental Procedure

SiC films were typically grown on Si-faces of 6H-SiC (0001) substrates. The substrates used in this study were either on-axis or off-axis (3–4° off from (0001) toward $<11\overline{2}0>$) provided by Cree Research, Inc. Films were all grown by GSMBE method under several conditions. The typical growth conditions are listed in Table I. The details of the deposition process can be seen in the accompanying report. During the growth of films, a RHEED pattern was monitored by the use of CCD camera and video recorder.

Table I. Typical Growth Conditions for the SiC films

Temperature	1050 °C
Si_2H_6 flow rate	0.1, 0.3 sccm
C_2H_4 flow rate	0.1–0.3 sccm
Si_2H_6/C_2H_4 flow ratio	1.0, 0.5
Growth rate	50–100 Å/hr

After growing the film, the sample was cut and glued face to face to make a cross-sectional TEM sample, followed by the thinning processes of grinding, dimpling and ion milling. Finally the sample was examined by a Topcon EM-OO2B operated at 200kV acceleration voltage.

C. Results

Figure 1 shows the cross-sectional image of the SiC film on off-axis (vicinal) 6H-SiC (0001) substrate. The substrate was oriented 3–4° off-axis towards <11$\bar{2}$0> as indicated by the arrow in the figure. Thus, there are periodical steps on the surface. The resulting film was generally cubic (3C) in structure and had a rough surface morphology due to three dimensional growth under the condition of a Si_2H_6/C_2H_4 ratio of 0.5. The magnified image of the island region can be seen in Fig. 2. The two islands (3C) which nucleated on the different terrace sites and are separated by a step can be clearly seen.
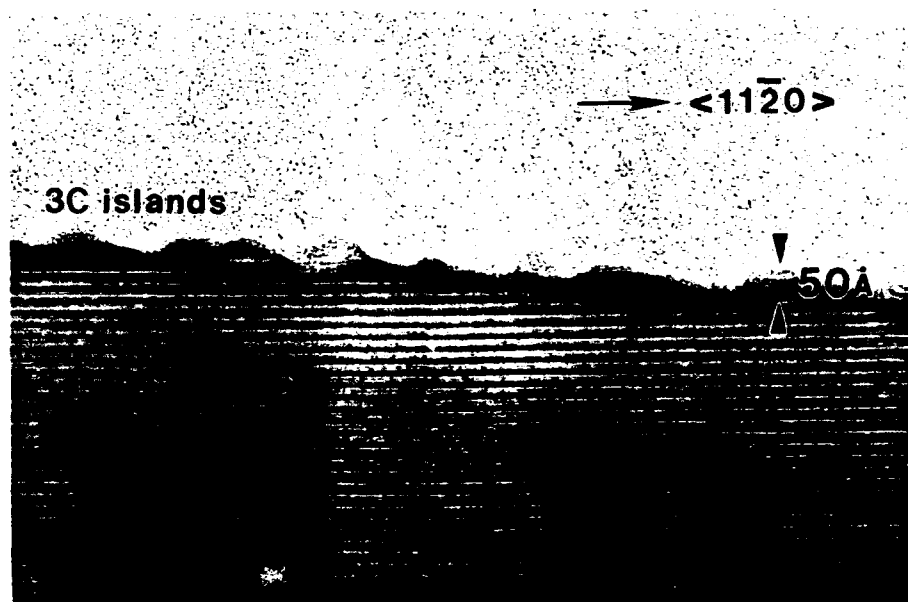

Figure 1. Cross sectional TEM image of 3C SiC islands on a 6H-SiC substrate off-axis towards <11$\bar{2}$0>.

The effects of vicinal orientation on film morphology were examined with the use of a substrate which was tilted 3–4° off (0001) towards <10$\bar{1}$0>. Figure 3 shows the result of growth under the same conditions as above on this substrate. A smoother surface can be observed compared with the material grown on the <11$\bar{2}$0> substrate, suggesting that steps play a role in affecting film growth. The exact mechanism is unknown but the differences in step geometry and chemistry appear to affect the film growth. The <11$\bar{2}$0> and <10$\bar{1}$0>

8

substrates have a zig-zag and a straight geometry of steps, respectively. Accordingly, each substrate may have a different bonding configuration at the steps. It should be addressed that investigating growth mechanisms in conjunction with substrate orientations will be done in the future.
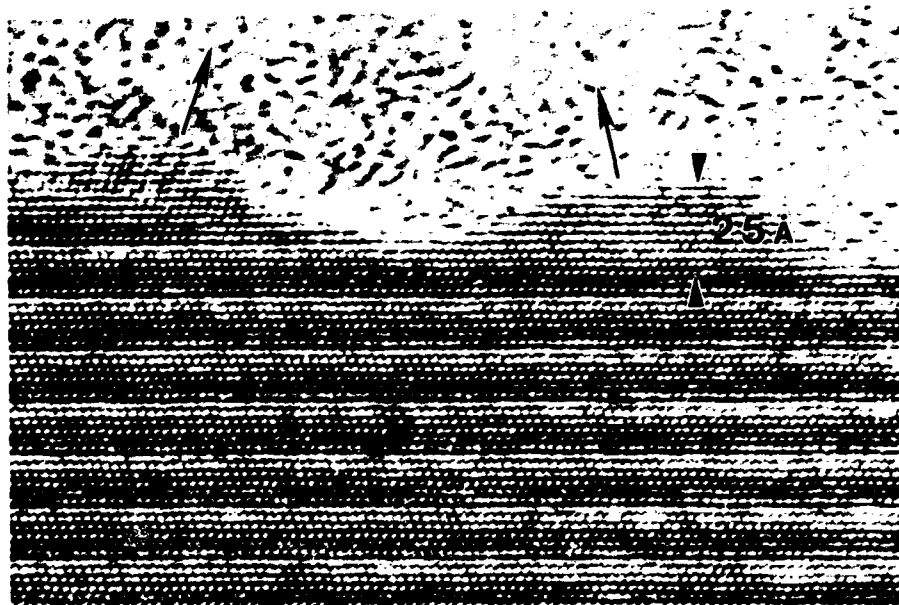

Figure 2.   HRTEM image of 3C SiC islands on a 6H-SiC substrate off-axis towards <11$\bar{2}$0>.
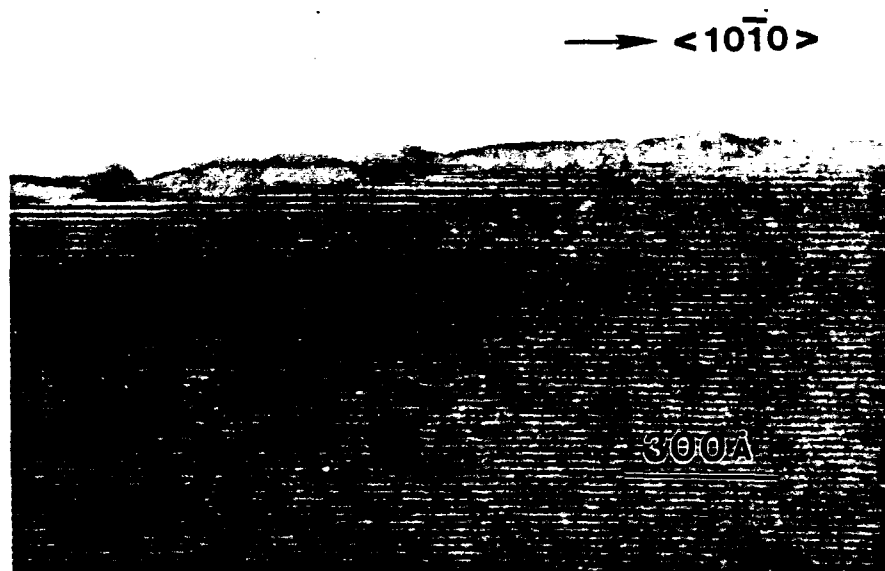

Figure 3.   Cross sectional TEM image of 3C SiC on a 6H-SiC substrate off-axis towards <10$\bar{1}$0>.

Under the different conditions in which the Si_2H_6/C_2H_4 ratio was 1.0 and the total flow rate was 6.0 sccm, a drastic change in film growth was observed. Figure 4 shows 6H-SiC film growth with a fairy smooth surface (almost identical to the substrate). It could be inferred the film thickness is ~120Å based on the previous study for the growth rates. However, it should be necessary to obtain the presence of a film by other techniques.
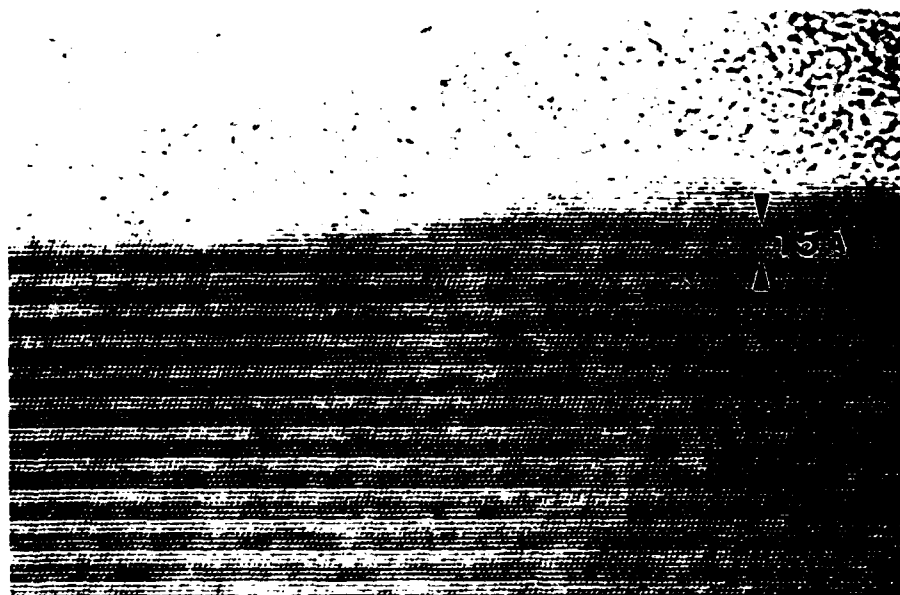

Figure 4.   HRTEM image of 6H-SiC film on an off-axis 6H-SiC substrate.

D.   Discussion

The drastic change in growth mode from three dimensional growth to two dimensional growth has been observed with the variation of the Si_2H_6 to C_2H_4 gas flow ratio from 0.5 to 1.0. The resulting film microstructures were also changed from 3C to 6H accordingly. The step flow type of growth might be enhanced. The possible scenario is that the surface migration distance of adatoms (or precursors) may be increased because of the change in surface chemistry as the film grows. It could be attributed to the Si terminated surface. At present the exact growth mechanisms under different growth parameters are continuing to be investigated through a combination of using a RHEED oscillation technique and HRTEM.

E.   Conclusion

The growth mechanisms of SiC films under several growth conditions have been discussed. The vicinal orientation of the substrate may play some role in the growth mode due to geometrical and chemistry related effects of the steps. Interestingly, the growth modes and polytype of films can be altered with the variations of feed gas ratio such as Si_2H_6/C_2H_4.

Pure homoepitaxial growth of 6H-SiC was observed for the first time. The step flow type of mechanisms are considered to be plausible for explaining the results. However, the proof of the presence of the films and further studies should be made to elucidate the growth mechanisms.

F. Future Research Plans

Several more depositions will be conducted under the different growth conditions. Gas flow rates and ratios will be especially to be focused on. The proof of the film existence should also be made with various techniques. *In-situ* RHEED study will continue to be used in studying the growth mechanisms. Since the importance of initial surface chemistry and structure is obvious, an attempt to better understand the nature of the substrate surfaces will be performed through XPS, TPD (temperature programmed desorption) and LEED methods. Finally, the control of polytype formation (2H and 4H) will be challenged on the basis of the theory obtained in this study.

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IV. Determination of the Diffusivity of Si, C, Al and N at the Interface of the SiC-AlN Diffusion Couple

A. Introduction

Silicon carbide has long been of interest because of its superior structural, thermal and electrical properties. High temperature and/or erosion- and corrosion-resistant wear parts, as well as optoelectronic and microelectronic semiconductor devices, are representative applications. Control of the physical and chemical properties of SiC via microstructural changes achieved by using different processing routes has been extensively studied for many years. The microstructural variables most frequently changed include the amount and the morphology of the various polytypes in the processed material, intentionally-introduced second and additional phases and additions of sintering aids which may or may not form a grain boundary phase. The processing temperature, impurity content, and sintering (or annealing) atmosphere affect the resultant microstructure. However, the primary material remains SiC. Another approach to property engineering involves the alloying of SiC with other ceramic compounds to alter, e. g., the band gap. This approach has also been of interest for several years.

One compound which has been reportedly alloyed with α(6H)-SiC (a_O = 3.08Å) is AlN (a_O = 3.11Å) due to the similarities in the atomic and covalent radii and the crystal structures. Diverse processing routes have been employed to achieve partial or complete solid solutions from these two compounds including reactive sintering or hot pressing of powder mixtures and thin film deposition from the vapor phase [1–12]. There exists, however, a difference in opinion among investigators regarding the occurrence and the extent of solid solutions in the SiC-AlN system at temperatures < 2100°C. As such, a research program has been initiated to determine the rates and extent of chemical interdiffusion between deposited monocrystalline AlN (0001) films and α(6H)-SiC (0001) substrates. The progress to date is described in the following sections.

B. Experimental Procedures

Sample Preparation. Samples were prepared in a modified Perkin-Elmer 430 molecular beam epitaxy (MBE) system. Aluminum (99.999%) was evaporated from a standard effusion cell. Activated nitrogen was achieved using an MBE compatible, electron cyclotron resonance plasma source. Single crystal AlN with very few planar defects was epitaxially deposited on vicinal α(6H)-SiC [0001] wafers manufactured by Cree Research, Inc. and cut off axis 3°–4° toward [11$\bar{2}$0]. Growth conditions for the films are presented in Table I.

Table I. Growth Conditions for the 2H AlN films on α(6H)-SiC(0001) substrates

Nitrogen pressure	2×10^{-4} Torr
Nitrogen flow rate	4–5 sccm
ECR microwave power	50 W
Substrate temperature	650°C
Growth rate	$\approx 0.1\mu m/hr$
Total growth time	7–8 hrs.

Transmission electron microscopy (TEM) (Hitachi H-800) photos have been taken of the 2H-AlN (wurtzite) film on the α(6H)-SiC substrate before annealing and show a smooth and abrupt interface. Several different precautions were taken in order to prevent contamination of the samples and to minimize the loss of the principal volatile components of aluminum and nitrogen. The samples were placed in a high density pyrolitic graphite crucible shown schematically in Fig. 1. The inside of the crucible was previously coated with SiC by heating

Figure 1. Schematic of a high density pyrolitic graphite crucible.

a mixture of Si and β-SiC inside the holder to 2000°C. The diffusion samples were placed inside this holder with the α(6H)-SiC(0001) face against the SiC coating. Bulk AlN squares were then placed on top of the deposited AlN. The holder was closed using a threaded lid and loaded into the furnace. The chamber was evacuated (2×10^{-6} torr) to prevent contamination during diffusion. N_2 gas (99.9995%), purified by a gettering furnace containing heated Cu

chips (Centorr Furnace model 2B-2O) was then introduced into the chamber at a rate of 500 sccm. The chamber was brought to atmospheric pressure and a flowing N_2 environment maintained throughout each diffusion anneal. Diffusion temperatures were reached in ~40 min. The samples were then removed for characterization. The N_2 gas, bulk AlN, and SiC coated crucible are not meant to aid in the diffusion. This was checked by a SiC-AlN standard which had not been annealed. The AlN intensities, as well as the SiC, in the standard were the same as the AlN and SiC intensities outside the diffused region. The samples were annealed within the temperature range of 1850°C–1940°C for a period of 25 and 50 hours. A complete listing of temperatures and times are given in Table II.

Table II. Annealing conditions used to date for the AlN/SiC diffusion couples

Temperature (°C)	Time (hrs)
1825	75
1825	100
1850	25
1850	50
1875	50
1875	75
1900	25
1900	50
1940	50

C. Results

The samples will be analyzed using special x-ray photoelectron spectroscopy equipment located at Oak Ridge National Laboratory.

D. Future Research Plans/Goals

The diffusion anneals will be completed using the procedure described above. Special care is being taken to ensure a flat AlN surface is achieved after the diffusion experiments and prior to the XPS depth profile studies. Light polishing with diamond paste is being used to produce a flat top surface if it is not present after the diffusion anneals. Additional studies to be conducted in tandem with the diffusion runs include: (1) the fabrication of solid solutions using MBE and the subsequent annealing at high temperatures to determine if either

14

segregation of the AlN and SiC occurs or if the solid solution is maintained, thus proving that it is an equilibrium phase and (2) the additional use of parallel electron energy loss spectroscopy to determine if interdiffusion can be discerned at any temperature.

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V. Design and Development of an Ultraviolet Double Heterostructure Light-emitting Diode

A. Introduction

Recent research efforts in the wide-bandgap semiconductor field have concentrated on the development of light-emitting diodes (LEDs) that emit in the blue and ultraviolet wavelengths. The III-V nitrides are promising candidate materials for the development of highly efficient LEDs that emit in this spectral range because they possess three favorable characteristics: (1) they all have direct transition band structures, (2) their transition band energy levels correspond to the UV and blue spectral range, and (3) they can be mixed to form solid solutions allowing for the tailoring of bandgap energies to specific wavelengths. Within the past several years, significant advances in GaN and AlN growth techniques have been achieved [1–10]. Consequently, high quality epitaxial films that exhibit remarkably improved surface morphologies can now be produced by CVD and MBE methods. Additionally, researchers have successfully doped the III-V nitrides and their alloys creating n-type (Si, Ge) doped films [11–13] and, more notably, p-type magnesium doped films [4,9,12]. These recent developments provide all of the material ingredients necessary for the fabrication of efficient blue and UV LEDs.

Some of the earlier LED designs were constructed of simple p-n junctions of GaN. These devices lacked the efficiency required for practical applications [13,16]. Further refinements on the device designs were developed to enhance the LED characteristics. By combining growth techniques leading to the construction of a double heterostructure single quantum well and doping the confining layers, the efficiency of the resulting LED could be further optimized by improving the carrier confinement and mobility. Recently, several successful attempts have been reported in the fabrication of double heterostructure (blue and UV) light emitting diodes [12–19]. All of these efforts have used either MOCVD or MOVPE growth techniques. Most designs are GaN based, using $Al_xGa_{1-x}N$ solid solutions for UV emissions, and $In_xGa_{1-x}N$ solid solutions for blue emission. All of the devices fabricated used sapphire substrates and either AlN or GaN buffer layers. A typical double heterostructure design is shown schematically in Fig. 1.

B. Future Research Plans

The light emitting diode to be fabricated using modified gas source molecular beam epitaxy is a GaN based double heterostructure consisting of two AlGaN confining layers separated by a GaN active layer. Selection of the GaN based system was governed by several factors. First, the quality of the films grown by GSMBE was considered. Currently, the highest quality films produced are AlN and GaN, and alloys composed of the two. At the

16

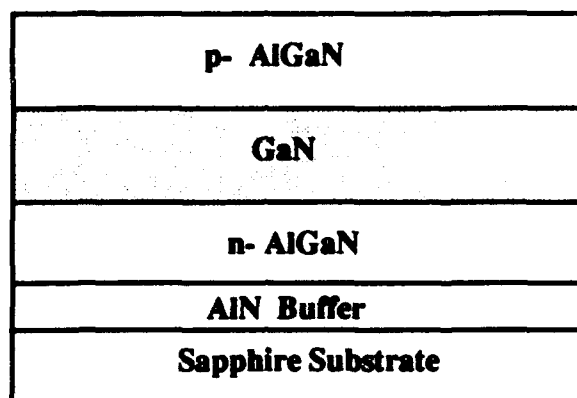| |
|---|
| **p- AlGaN** |
| **GaN** |
| **n- AlGaN** |
| **AlN Buffer** |
| **Sapphire Substrate** |

Figure 1. Schematic of a typical double heterostructure.

present time, we are still investigating ways to optimize the quality of InN and InGaN growth by modified gas source MBE. Once we are satisfied with the quality of the epitaxial grown InGaN/InN films, we will expand our device studies to incorporate those films. Secondly, the electrical characteristics of the AlN and GaN films were considered. Of the two, GaN provides more favorable carrier mobilities and electrical resistivity [20]. Additionally, in our experience, GaN accepts p-type (Mg) dopants more readily than does AlN. Having selected the AlGaN/GaN system for the basis of the LED and using GaN as the active layer, the emitted light will exhibit a wavelength in the UV-spectral region (at a bandgap energy = 3.45 ev corresponding to 360nm). The choice of substrate is α-SiC which will provide for the growth of better quality films than those grown on sapphire [20].

The first stage in the LED construction is directed at attaining compositional control of the $Al_xGa_{1-x}N$ solid solution and control of the deposition rate to achieve the desired confinement layer thickness. The study will include alloy compositions ranging from $0.1 < x < 0.4$. The composition will be controlled by varying the cell temperatures of the Al and Ga Knudsen effusion cells. Previous studies conducted by our group showed that solid solution films can be grown by GSMBE over the entire range of $0 < x < 1$. Characterization of the alloy film compositions will be performed using a Scanning Auger Microprobe. The thickness of the films will be determined by SEM and ellispometry techniques.

The second stage in the development of the UV LED, once the growth parameters have been determined for achieving the desired composition and growth rate, will be the deposition of the underlying structures for the double heterostructure designs. Various growth conditions will be used to control such designs encompassing active layer thickness and AlGaN doping with Mg and Ge. Selection of the active layer thickness will be made with consideration of (1) strain induced bandgap shifts, (2) critical thickness of the GaN layer, and

(3) composition of the alloy confinement layers [21–23]. After the structures have been grown, the devices will be fabricated using reactive ion etching for mesa formation. Optical characterization of the final LED designs will include photo- and cathodo-luminescence.

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